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# Required coefficient of friction during level walking is predictive of slipping

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ABSTRACT

The required coefficient of friction (RCOF) is frequently reported in the literature as an indicator of slip propensity. This study aimed to further develop slip prediction models based on RCOF by examining slips under moderately slippery conditions where the RCOF was approximately equal to the available coefficient of friction. Baseline RCOFs were found for normal walking trials and then an unexpected slip was introduced with a moderately slippery boot-floor contaminant combination for thirty-one subjects. Slip outcomes (i.e., whether a subject experienced a slip) were assessed based on the displacement of a marker placed on the heel. A logistic regression analysis was used to model the impact of RCOF on slipping. Results showed that subjects who walked with a greater RCOF were found to have a higher probability of slipping. The predicted probability of a slip across the RCOF ranged from 3% to 95% and an increase of 0.01 in RCOF was associated with a slipping odds ratio of 1.7. Thus, modest differences in RCOF can have a dramatic impact on slip propensity. This study shows that RCOF can be a sensitive and valid predictor of slipping in realistic frictional environments.



## 1. INTRODUCTION

Slip, trip and falling accidents account for approximately 27% of all non-fatal occupational injuries [1] and 17% of all fatal injuries [2] in the United States. The Centers for Disease Control estimates that falling accidents cost the US economy $180 billion in 2013 ($169 billion for non-fatal falls [3] and $11 billion for fatal falls [4]). Slips are a common initiating event accounting for approximately 40% of occupational falling events [5].

From a biomechanical perspective, slips occur when the frictional properties of the footwear-floor interface are not sufficient to counter the biomechanical requirements of walking. Probabilistic slip-prediction models have been developed based on the difference between the available coefficient of friction between the outsole and floor surface (ACOF) and the required coefficient of friction or RCOF due to the biomechanics of gait (Eq. (1)) [6–9]. In these studies, ACOF was measured using a tribometer or slip-tester, while RCOF was calculated from ground reaction forces during unperturbed walking. One limitation in these previous studies is that the difference between ACOF and RCOF is typically used as a single predictor of slipping [6,8–10]. By combining ACOF and RCOF into a single predictor, the individual contributions of ACOF and RCOF remain unknown. Also, previous research has typically developed these probabilistic models based on a wide range of ACOF values [10–12] and the sensitivity of these models to individual differences in RCOF, which can be rather small, has not been quantified. While RCOF is simply a ratio of the shear and normal forces during the stance phase of gait, the dynamics of locomotion that lead to these forces, and subsequently the RCOF, can be complex [13,14]. Therefore, the robustness of this single predictor model is questioned.

$$Slip_Risk = \frac{e^{\beta_0+\beta_1*(ACOF-RCOF)}}{1+e^{\beta_0+\beta_1*(ACOF-RCOF)}} \quad (1)$$

The current state of slip prediction models remains inconclusive regarding whether an individual's RCOF is an important predictor to slipping. Some studies have found that ACOF on its own can predict slipping accidents, which may indicate that ACOF is the main contributor to slipping and that RCOF may not be needed in these models [8,11]. Hanson et al. found that increasing the walkway inclination angle led to a substantial increase in RCOF (increase of ~0.14 for a 10° inclination and increase of ~0.25 for 20° inclination) and an increase in slip rates, which suggests that RCOF contributes to slip outcomes [10]. However, Hanson et al. did not directly quantify the impact of RCOF on slipping and did not develop a slip prediction model based on the RCOF. Thus, an

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important gap in the literatures exists regarding how RCOF influences slip outcomes.

Several biomechanical factors influence individual RCOF. For example, RCOF has been found to be positively correlated with step length [13], negatively correlated with cadence [13], positively correlated with heel contact velocity [14] and negatively correlated with whole body translational acceleration [14]. Furthermore, RCOF has been observed to be lower in older adults than younger adults, primarily due to shorter step lengths [13]. Lastly, RCOF increased when the quadriceps muscle group was fatigued [15] and decreased when anticipating a slip event [16]. Many of these reported differences were relatively modest (differences of about 0.03–0.06) and it remains unclear if these differences are significant. Research that quantifies the relationship between RCOF and slipping outcomes would add important context to these previous studies.

This study aims to quantify the ability of individual RCOF to predict slip outcomes in moderately slippery conditions. We hypothesize that even moderately higher RCOF values will be associated with more frequent slipping.

## 2. Methods

### 2.1. Subjects

Thirty-one subjects were recruited to participate in the study including 14 female subjects (mean age: 24.4 ± 5.18 years; mean height: 170 ± 6.00 cm; mean mass: 77.4 ± 22.3 kg; mean boot size: 7.6 ± 0.76 US Men's Sizing) and 17 male subjects (age: 24.0 ± 4.19 years; height: 177 cm ± 7.89 cm; mean mass: 76.3 ± 17.1 kg; mean boot size: 9.6 ± 1.2 US Men's Sizing). Subjects were screened over the phone to initially determine eligibility in the study. Subjects were excluded if they reported a weight of over 136 kg; height over 1.94 m; age outside of a range from 20 to 35 years; history of neurological problems; orthopedic problems within the previous 3 years; osteoporosis; cardiovascular problems; balance or dizziness problems; taking cardiovascular, neurological or vestibular medication; or had cardiovascular, orthopedic, or ear surgery. In addition, female subjects were asked to take a pregnancy test and were excluded if the test was positive. Participants also needed to be able to wear a boot size between 7 and 12 on the US men's footwear size scale. Two subjects were removed from the analysis because they substantially changed their gait or frequently looked down when approaching the contaminant, indicating that they were anticipating a slip. All subjects provided informed consent prior to participation, and the study was approved by the University of Pittsburgh Institutional Review Board.

### 2.2. Procedure

Prior to testing, participants were fitted with tight fitting clothing, 79 reflective markers and a safety harness. The only relevant marker for this study was the inferior-most point of the back of the boot. Details regarding the full marker set can be found at [17]. Kinematics of the reflective markers were collected using a motion capture system (Vicon T40S, Oxford, UK), while ground reaction forces during walking were collected with a force plate (Bertec 4060A, Columbus, OH). Subjects were randomly assigned to wear boots with one of three outsole material formulations. The different boot outsole materials used different formulations of synthetic rubber, which gave them different hardness levels. The boots had the same tread pattern and surface roughness (Fig. 1). The reason for using multiple boot outsole designs was because the present study was part of a larger study that was examining the impact of subtle changes in outsole material on slipping. After subjects were assigned to a pair of boots, they completed five baseline trials. If the subject missed the force plate with their left boot or hit the force plate with both feet, then an additional baseline trial was completed. Subjects were told to walk at a comfortable walking pace and walking speed was not controlled by the research team. The subject walked approximately 5 m preceding the force plate and 5 m after the force plate so that they reached steady state walking prior to striking the force plate (Fig. 2). Participants then experienced an unexpected slip event where a glycerol and water solution (50% glycerol and 50% water by volume) was placed on the floor without the subjects' knowledge. The contaminant was selected based on preliminary ACOF testing that revealed that this contaminant (along with the selected boots and flooring) was likely to cause some but not all subjects to slip. Participants experienced up to two additional slip trials after the first but this data was not analyzed in the present study. Boots were washed with detergent and water, rinsed and air-dried between testing sessions to ensure that they were clean for each testing session consistent with previous studies by our group [17,18].

**Fig. 1.** Picture of tread pattern (top), heel region (middle) and boot upper design (bottom). The close-up view of the heel region is consistent with the circle marked on the top figure.

The hardness, roughness and ACOF were characterized for the three boot outsoles. The average roughness (Ra), RMS roughness (Rq) and average peak-to-valley roughness (Rz) of the posterior-